Wireless Sensor Networks Routing over Zones

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***Abstract*—In this paper, we propose a routing protocol for wireless sensor networks based on a two-level, zone-based architecture. DV is applied in both intra-zone and inter-zone routing, based on the hop metric. Our solution is original because it is instrumentation-free (sensors are both localization and energy unaware) and completely distributed. We show performances of the proposed algorithm evaluating the overhead generated by the construction of the infrastructure needed in routing. Simulations for MICA2 sensors have given us indications on the energy consumption - almost 4*10^{-4}% of the total battery capacity, on the scalability property of the algorithm and on the memory size of the data structure used for routing - almost 13% of the RAM memory. Moreover, memory constraints allow us to determine a lower bound for the number of zones.**

***Index Terms*—wireless sensor networks, hierarchical routing, zone architecture**

I. Introduction

Wireless sensor networks (WSNs) constitute one of the recent technologies which are used to monitor and analyze large-scale, real-world phenomena, a bridge between the physical world and the information technology's need of situational awareness. One major requirement of WSNs is information transmission: sensors communicate useful environmental data to one or more resourced base stations (BS or sinks). The simplest WSN topology allowing this communication is the single-hop star, feasible when all sensor nodes can communicate directly with the sink. However, when deployed over large areas, nodes are generally distant from the base stations, therefore single-hop star architectures become limited. In multi-hop networks, one critical point is defining an appropriate route for each message intended for the base station. Moreover, large-scale deployments are frequently used in sensor networks and virtual architectures need to be designed. This challenge justifies our contribution on hierarchical routing approaches for communications in wireless sensor networks. The network architecture on which our routing protocol is based is constructed on top of zones. The detailed algorithm and its evaluation are given in [1]. In section 3, we remind only the main idea. Compared to other organizational techniques - see section 2 - like clustering, generally assuming network instrumentation, our solution is instrumentation-free (sensors are both location and energy unaware) and completely distributed. Our proposal of a two-level routing infrastructure over this virtual architecture is presented in section 4. Wireless sensor networks are submitted to particular constraints of energy, and size of the storage space; moreover WSN applications generally need large-scale deployments. Considering these constraints, we evaluate the construction of our routing data infrastructure in section 5. The last section concludes our work.

II. Routing challenges in wireless sensor networks

One general solution that responds to the large scale deployment of WSNs is network structuring. The most frequently employed approach is clustering.

Clustering has been inspired from the cluster networks in which particular nodes, called cluster heads, have additional functionality of managing cluster formation and maintenance. In sensor networks, these functionalities are associated to more powerful nodes, like in LEACH [2], APTEEN [3], CMLDA [4], Hierarchical Clustering [5], and HEED [6]. All clustering approaches assume that cluster heads can communicate directly (in one hop) with other cluster-heads, or possibly directly with the base station. We may infer that the underlying networks are heterogeneous, some nodes having more (or at least adaptive) transmission power and more energy. Moreover, if energy-balancing techniques are used, like cluster rotation, this requires that all network nodes should potentially be able to reach cluster heads or even the BS in one hop. Routing is out of question in this architecture because of the strong hypothesis on node accessibility. Some clustering approaches are hierarchical (Hierarchical Clustering), cluster heads forming a hierarchy for packet communication. Once again, in this approach, the cluster heads are supposed to be able to communicate directly and no communication protocol is given to explain the way in which this hierarchy is exploited. The challenge in cluster formation is defining the appropriate number of cluster heads and their distribution: few cluster heads generate important cluster management overhead, whereas geographically close cluster heads do not allow good coverage of the network. Some distributed approaches forming clusters exist (HEED, Hierarchical Clustering, LEACH), but they are tributary to the distributed aspect of the algorithm and can not assure good properties for the cluster head number and their distribution. C-LEACH [7] and C^2E^2S [8] - combined solutions between cluster and chain strategies - are centralized approaches which make use of the BS to produce better organization, based on node energy. More generally, centralized approaches can not be applied to WSN systems, because of the important overhead generated by the construction of a global network view at each sensor node.

When geographical node position is required to form groups of sensors, two other classes of architectural approaches can be identified: the grids or the zones (HPAR [9], VGA [10], TTDD [11]). In TTDD, nodes are grouped in zones and dissemination nodes collect data from source nodes and send it to the sink. Node geo-localization may be an expensive mechanism for largely-deployed networks. The GPS may be partially used (only beacon nodes are location-aware), but geo-localization strategies may generate important computation overhead and error. Moreover, GPS solutions are not available in any type of environment.

All previously cited works tend to find architectural solutions in order to maintain a structured view of networks, enabling easy communication exchange between nodes in transmitting the sensed information to the BS. Every proposed solution is either based on particular hypothesis (geo-localization of node, transmission power control, direct BS access) or makes use of centralized algorithms needing permanent energy information over nodes or links. We assume these approaches difficult to implement and to embed in real wireless sensor networks, characterized by a high level of decentralization, low resources and small storage capacity. These arguments justify our routing protocol for WSNs. We make no assumptions concerning node localization, adaptive transmission power, or energy level awareness. Our approach is completely distributed, based on a neighboring discovery protocol and virtual zone construction.

III. Virtual network architecture

Routing in largely-deployed wireless sensor networks needs network structuring, in order to avoid energy waste when flooding the network with packets addressed to particular targets: the base stations or other well-identified sensor nodes. We propose an inexpensive algorithm which forms disjoint zones using the basic metric: the number of hops. We do not intend to make this construction complex, using energy metrics (of nodes or links) because this kind of information is highly dynamic and its update would generate important control overhead. The aim of our structuring is providing

- local views for routing inside zones, because only the nodes in the proximity of the sensor containing the data to be sent may be involved in the packet's routing and
- global view over all zones, because only the zones in the direction of the target's zone are concerned in the routing.

Our hypotheses are the following: nodes are randomly deployed, localization unaware, energy unaware, bidirectional communication links are assumed, no transmission power variation is available. Each node has a unique identification assigned.

The zone partitioning algorithm takes as parameters the zone radius (measured in number of hops `R`) and the number of zones (`nZ`). The detailed algorithm is given in [1], here we briefly describe the principle. `nZ` nodes are chosen as inviting nodes, which have the initiative of propagating the zone invitation packets. Concurrent invitation packets are dealt with at the receiver using different packet types: INVITATION, DISAGREEMENT. Inviting nodes do not have another role besides initiating the zone construction; this is the reason why our algorithm can not be classified as clustering method. Moreover, it does not use any localization information on nodes, so it can not be considered grid or zone structuring according to their definition given in the previous section. The best choice of `R` and `nZ` is a difficult problem: the network should be properly sectioned and every node should join a zone. Even though we do not address this matter here, a lower bound for the number of zones is determined, based on the memory metric.

Our zone partitioning approach defines two types of nodes: border (at the frontier with another zone) and normal. Every node (normal or border) has an internal routing table (of its zone) while every border node constructs a border-table with information necessary for the inter-zone routing phase. Consequently, one entry in this border-table (*BorderT*) contains the following information:

- the identification of the neighboring zone (*neighZoneId*),
- the list of all border nodes in each of its neighboring zones (*borderNodeIds*).

IV. Zone Routing

Our routing approach is inspired from the adhoc networks: no predefined infrastructure exists. Proactive solutions seem to us adaptable to the aimed WSN applications, in which little sensor node mobility is involved - the sink mobility is a more frequent case, which is not addressed here. We use the hop metric, which is stable throughout the lifetime of the network: updates need to be made only when new sensor nodes join the network or when existing nodes leave it.

Our routing protocol is table-based and zone-based, the table construction being done in two phases, presented next: the intra-zone routing table construction and the inter-zone routing table construction.

A. The intra-zone routing table

The intra-zone routing table is constructed based on the DV algorithm (Bellman-Ford).

Two well-known table-driven algorithms are used for adhoc routing, Distance-Vector (DV) and Link-State (LS). Distance vector protocols use distance calculation plus an outgoing network interface (a vector) to choose the best path to a network destination. Link-State protocols track the status and connection type of each link and produce a calculated metric based on these, which help to choose the best path. We chose DV because it needs less computation resources and smaller storage space than LS. Distance vector routing protocols are efficient for small environments; on the other hand, link state convergence occurs faster than distance vector convergence.

An entry in this intra-zone routing table, denoted *IntraZoneRT*, contains the following information:

- the destination node (*destNodeId*),
- the next hop (*nextHopId*),
- the metric (*M*) - computed in number of hops,

- the type of the destination node, normal or border (*nodeType*),
- moreover, if the destination node is a border node, the entry contains the list of neighboring zones (*neighZoneIds*).

This construction exploits the principle of DV algorithm on a smaller number of nodes (those of a zone). The maximum hop count method (also used in the RIP protocol) has been used in order to avoid routing loops.

B. The inter-zone routing table

The principle of the DV algorithm is applied between zones to form the inter-zone routing tables. These are necessary for the border nodes which are responsible to relay packets between zones. In order to avoid redundant computation and thus flooding border nodes with similar information, a particular border node is chosen per zone. It is called *chief node* - its type is identified by `BORDER-CHIEF`. It has the highest identification between the border node identifications in the zone; this information can be extracted from the *IntraZoneRT* routing table. The chief node computes the inter-zone routing table and forwards it to all the other border nodes of the zone. The choice of the chief node may lead to asymmetric energy consumption, which may be adjusted by natural rotation solutions.

One entry in the inter-zone routing table, denoted *InterZoneRT*, contains the destination zone (*destZoneId*), the next zone (*nextZoneId*) and the zone metric (*zoneM*).

The metric used in the *InterZoneRT* construction is the *zone metric*. It evaluates the cost of crossing a zone and is defined as the average length (in number of hops) of the longest paths between any two nodes of the zone. The *zone metric* is computed during the *IntraZoneRT* construction.

The packets exchanged in this table-construction phase contain the following information: the source node (*srcId*), the next hop (*nextHopId*), the zone of the source node (*srcZoneId*), the subject (which may be COMPL_TABLE: complete the table or UPDATE_TABLE: update the table), the zone table (*InterZoneRT*) and the final destination (*finalDestId*).

When receiving a routing control packet *packet*, a node processes it depending on its type (NORMAL, BORDER or BORDER-CHIEF). A normal node forwards the packet towards the final destination; a chief node updates the *InterZoneRT* routing table and sends updates to some border nodes of its zone and to the border nodes of the neighboring zones. Finally, a border node forwards the packet to the chief node of its zone, if the packet comes from a border node of a neighboring zone. Otherwise, if the border node is a final destination, either it updates the table, or it forwards the packet to the border nodes of the neighboring zones; else, it sends the packet to the final destination.

V. ROUTING EVALUATION

The J-Sim simulator[1] [12] has been our choice for the routing protocol experimentation in sensor networks. Built upon the concept of autonomous component programming model, it allows defining customized sensor environments (sensor's layers and the communication infrastructure). Among other several network simulation platforms - Tossim [13], NS-2 [14] (adapted for WSNs) - J-Sim looked the most appropriate for our experiments, because it allows large-scale simulations and offers the possibility of integrating one's own routing protocol. J-Sim is developed entirely in Java and uses Tcl as script language to facilitate scenario setups.

The simulations were performed on a large area of 1500m over 1500m. The node's maximum transmission range was set to 150m. The network size was varied between 400, 500 and 600 nodes.

In order to evaluate the data infrastruction construction needed for the routing protocol, we considered four metrics: the overhead, the energy consumption, the scalability and the memory capacity. Each of these measures is influenced by both the zone construction and the routing table construction. We present results separately for each phase. One particular evaluation metric is the generated overhead. We estimate it by both the number of sent and received packets and we infer the energy consumption, on the basis of the energy model of the MICA2 sensors [15] - radio reception drains 10 mAh, radio transmission drains 27 mAh while data transmission rate is 38400 bits/s and the initial battery energy is 2900 mAh. In this energy evaluation, we neglected the computation cost, generally very small compared to the transmission/reception cost (for MICA2, 8mAh are drained by CPU computation).

A. Overhead

We define the overhead as the cost in terms of number of control messages exchanged during both zone and routing table construction.

1) Zone construction overhead: The overhead in zone construction depends on the number of zones (`nZ`), and is independent of the zone radius `R`, once the error ratio (the number of unassigned nodes) is close to zero. The average number of sent messages per node varies from 3 to 5,5 when the number of zones varies from 5 to 25. The average number of received messages per node varies from 16 to 19. These results and more comments on the zone construction evaluation are given in [1].

2) Routing overhead: The most costly operation in the routing algorithm is the routing table construction. Figures 1 and 2 show the average number of sent and received packets per node, respectively, for the same 500-node network. The variation of the zone radius has the same effect as previously: when the error ratio is close to zero, no more overhead is produced when increasing the zone radius.

B. Energy consumption and scalability

We also estimated the energy consumption during the two phases, zone and table construction when varying the size of the network, from 400 to 600, for a fixed zone radius, `R`=15, and for the number of zones (`nZ`) varying between 10, 15 and 20. At the same time we evaluated the scalability of

[1]http://www.j-sim.org/

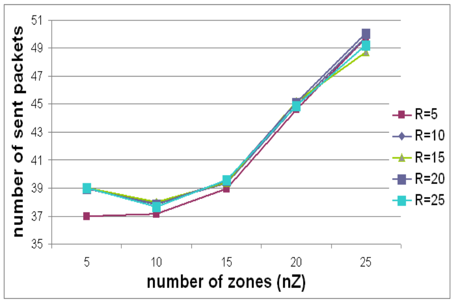

Fig. 1. Average number of sent packets per node during Routing Tables Construction for 500-node deployment

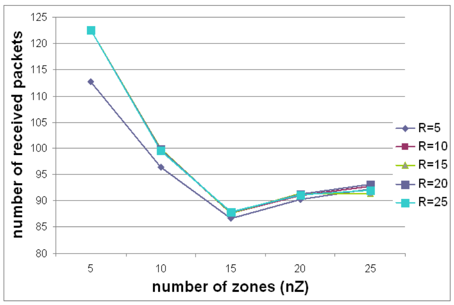

Fig. 2. Average number of received packets per node during Routing Tables Construction for 500-node deployment

the algorithm: no major degradation in performances should be identified, even when a large number of sensor nodes is involved.

Figure 3 shows the average percentage of the battery consumption per node during the setup phase of the protocol (covering both zone and routing tables construction). The energy model of the MICA2 sensors cited previously is applied. These computations depend on both the number of received and sent packets.

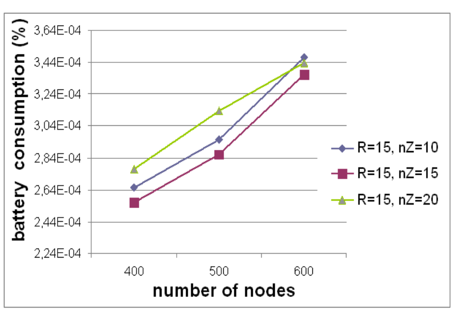

Fig. 3. Battery consumption based on the characteristics of MICA2 sensors

We can note little variation in the number of sent packets when the number of nodes is increased (40 to 49 for 15 zones, and 45 to 51 for 20 zones). This fluctuation is slightly more important (in percentage) for the number of received packets. More packets are received than sent, because of the radio communication model used in wireless networks (one sent packet may be received by several active nodes in the source node's vicinity). The total energy spent in communications varies sublinearly with the number of nodes which gives good scalability property to the algorithm.

C. Memory capacity

One other important evaluation metric for the WSN routing protocol that we propose is the size of the data structure used for routing. Using table-driven algorithms may need important memory space in the context of largely-deployed networks. We reduce already this complexity by the two-level routing tables that we construct. Next, we are interested in the space complexity, in terms of number of bytes occupied by the involved data structures. As far as we know, no other routing mechanism proposed in literature for wireless sensor networks considers this metric.

The formula computing the size (in bytes) for the routing data structures is given in Table I, for `N` deployed nodes, when `nZ` zones are constructed, each zone having in average `nB` border nodes.

	Zone Construction	Routing Table Construction
Border	(4+6*(nB/nZ))*2	(3*nZ+1+6*N/nZ)*2
Normal	4*2	(1+6*N/nZ) *2

TABLE I
THEORETICAL MEMORY SIZE (IN BYTES) FOR ROUTING DATA STRUCTURES

We experimentally evaluated the size needed for the data structures used by the routing algorithm (for a 600-node network, nZ=15, R=15). These experimental results confirm the estimation given in the general case. An average of 4Kb per node would be necessary to save data information for routing, which represents almost 13% of the RAM memory of a standard Mica2 sensor node.

D. Lower bound for the number of zones

The previous metric does not only estimate the size of the needed data structure in order to assure pro-active routing based on routing tables; it also gives a lower bound of the number of zones. This computation is based on a memory limit imposed for sensors in respect with the total memory capacity of a sensor. Depending on technologies, this total capacity may vary, therefore we make the following assumption: nodes technically dispose of `MEM_RAM` RAM memory capacity. Obviously, only a fraction of the total available memory can be used for protocol data structures. We denote it by the `MAX_MEM_PRCTG` percentage (%). Considering the theoretical memory capacity needed by the protocol for a normal node, we have

$10 + 12 * \frac{N}{nZ} \leq MEM\_RAM * MAX\_MEM\_PRCTG$

This gives a lower bound for the number of zones,

$$nZ \geq \frac{12 * N}{MEM\_RAM * MAX\_MEM\_PRCTG - 10}$$

We neglected in our estimation the memory capacity for the border nodes. Meanwhile, memory constraints for border nodes can be included by varying judiciously the `MAX_MEM_PRCTG` constant.

E. Comparison with other hierarchical approaches

Similar works proposing routing over particular sensor network structures exist as cited previously. Direct and objective comparison of results is difficult to assess for several reasons:

- different hypotheses are made - network instrumentation (through sensor positioning systems), network heterogeneity (concerning communication range),
- simulators are not the same - LEACH and APTEEN use an extension of the NS-2 simulator which was not initially designed for sensor networks (other works do not cite their implementation tool). Our choice was the J-Sim simulator, designed explicitly for sensor networks.

While imposing standard implementation tools is still possible, in spite of the cost of code migration, the differences in hypotheses is a serious problem which prevents us from real comparison.

However, remarks can be made concerning general trends in our solution, compared to similar existing works:

- our solution is neighboring-based (completely distributed) opposed to centralized ones (like some graph approaches),
- our solution to maximize the network lifetime is based on the number of radio hops (no communication overhead is involved), while several existing works are based on energy (involving information exchange),
- our virtual network architecture, zone-based, is not costly compared to cluster organization which implies maintenance overhead (to avoid cluster head exhaustion).

There are points of similarities in the strategy of our routing protocol over zones and the ZRP [16] protocol. The latter is proposed for ad-hoc networks, which prevented us from including it into the related work. However, it presents some similarities with our approach and we present here the differences. In ZRP, each node maintains its own routing zone, defined by the nodes whose minimum distance in hops from the node in question is no greater than a parameter referred to as zone radius. This implies that the routing zones of neighboring nodes overlap. This is not the case in our approach, zones being completely disjoint. ZRP proactively maintains routing information for a local neighborhood, while reactively acquiring routes to destinations beyond the routing zone. We use proactive approaches, for both inter and intra zone routing.

VI. CONCLUSION AND PERSPECTIVES

Energy consumption and data storage are two main features to optimize in the design of routing protocols for wireless sensor networks. We address in this paper a particular class of WSNs, in which some nodes can be id-addressed, like in sensor-based guidance systems. We propose a routing protocol based on a two-level, zone-based architecture. DV is applied in both intra-zone and inter-zone routing, based on the hop metric. No particular instrumentation of the network is required: sensors are location unaware, energy unaware, and no variation in their transmission power is assumed. We show performances of the proposed algorithm evaluating the overhead and the behavior of the algorithm when increasing the network size. Simulations using the characteristics of MICA2 sensors allowed us to estimate the energy consumption - almost $4 * 10^{-4}\%$ of the total battery capacity, and the memory capacity needed for the routing tables - almost 13% of the total memory. Another interesting result that we infer from the memory metric is the lower bound for the number of zones in the construction of the network architecture. Future work will analyze the feasibility of this algorithm in the context of an emulator or of a real sensor network platform experimentation.

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